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THERMAL MANIKIN AND MATHEMATICAL MODELING EVALUATION OF MILITARY HEAD-WORN COVERS

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THERMAL MANIKIN AND MATHEMATICAL MODELING EVALUATION OF MILITARY HEAD-WORN COVERS

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14. ABSTRACT

This report outlines biophysical properties of two different military head-worn covers, a prototype Afghanistan military cover and the current issue US Army patrol cover. This work describes the methods for calculating their biophysical inputs based on a whole human ensemble, and shows modeling results of the predicted thermoregulatory response differences between the two covers. Biophysical assessments show negligible differences between the prototype Afghanistan military cover (AF) and the current issue US Army patrol cover (US). Thermal resistance values were comparable between the two (AF; 0.12 and US; 0.12 [m2K/W]: 0.79 and 0.74 clo units). Evaporative resistance values were also similar (AF; 15.78 and US; 15.94 [m2Pa/W]: 0.47 and 0.44 permeability indices). Thermoregulatory modeling showed no differences over a two hour (120 minute) period during both rest and moderate walking activity (< 1%). This work concludes that from a biophysical and predicted thermal stress perspective there is no significant advantage of one cover versus the other.

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EXECUTIVE SUMMARY

The purpose of this work is to make scientific comparisons between a prototype Afghanistan military cover with an additional fabric liner to the current design cover that does not include the added fabric liner (US Army patrol cover).

This report outlines biophysical properties of two different military head-worn covers, a prototype Afghanistan military cover and the current issue US Army patrol cover. This work describes the methods for calculating their biophysical inputs based on a whole human ensemble, and shows modeling results of the predicted thermoregulatory response differences between the two covers.

Biophysical assessments show negligible differences between the prototype Afghanistan military cover (AF) and the current issue US Army patrol cover (US). Thermal resistance values were comparable between the two (AF; 0.12 and US; 0.12 [m^2K/W]: 0.79 and 0.74 clo units). Evaporative resistance values were also similar (AF; 15.78 and US; 15.94 [m^2P_a/W]: 0.47 and 0.44 permeability indices).

Thermoregulatory modeling showed no differences over a two hour (120 minute) period during both rest and moderate walking activity (< 1%).

This work concludes that from a biophysical and predicted thermal stress perspective there is no significant advantage of one cover versus the other.

INTRODUCTION

The US Army has long used thermal manikins and thermal model component level testing methods for evaluation of clothing and individual equipment (CIE) worn by military service members [1]. The scientific evaluation of CIE includes three main areas: biophysical evaluations, biomedical modeling, and human research studies. Typically the first step in these evaluations are conducted within a lab setting without accessing human test volunteers (i.e., biophysics and modeling). Direct biophysical data evaluations can be helpful in showing a quantitative value comparisons from one ensemble or component item to another [2]. However, a more informative approach is to combine these measured values with thermoregulatory models. These models enable predictions of thermoregulatory responses based on different individuals, as well as varied environments, clothing, or activity levels [3].

Within the US Army Research Institute of Environmental Medicine (USARIEM), the Biophysics and Biomedical Modeling Division (BBMD) has capabilities for conducting biophysical assessments at the material level (i.e., a fabric) using a sweating guarded hot plate), for component items (e.g., headgear, gloves, boots), using thermal manikin components, e.g., head, hand, or foot manikins; as well as whole-system level (i.e., full ensemble) tests using whole-body thermal manikins. Each of these systems are operated and maintained within climate controlled environmental chambers at USARIEM.

This report: 1) describes the biophysical properties of two different military head-worn covers, 2) describes the methods for calculating their biophysical inputs based on a whole human ensemble, and 3) models the predicted thermoregulatory response differences between the two covers.

METHODS

This study compared the biophysical test results between a nude manikin model head, a prototype Afghanistan military cover, and current the US Army patrol cover. This data was then modeled and compared to understand the thermal differences between the two covers and in relationship to the absence of a cover.

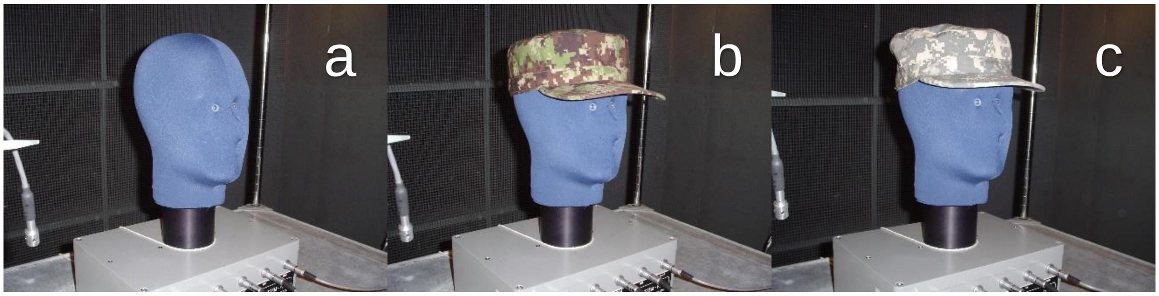
Materials

a) Nude thermal manikin model head (NUDE) – Figure 1a

b) Prototype Afghanistan military cover (AF) – Figure 1b

c) US Army current issue patrol cover (US) – Figure 1c

Figure 1. Sweating thermal manikin head (a), prototype Afghanistan military cover (b) and US Army current issue patrol cover (c)



Materials were tested using a sweating thermal manikin head (Model: “Icabod” - Thermetrics, Seattle, WA http://www.thermetrics.com/), located within an environmentally controlled climate chamber at the US Army Research Institute of Environmental Medicine (USARIEM). The sweating thermal manikin head is comprised of 6 independently controlled zones (forehead, head back, face, neck left, neck right, and neck front) (Figure 2).

Clothing Biophysics

Biophysical assessments were conducted to determine the thermal resistance (R_t; m^2K/W) and evaporative resistance (R_{et}; m^2Pa/W), of each of three conditions (nude, Afghan, and USA). Testing was conducted according to American Society for Testing and Materials (ASTM) standards (ASTM F1291-16 and F2370-16) [4-5]. Measures of R_t and R_{et} were then converted in units of clo ($1\ clo = 0.155\ [\mathrm{m^2K/W}]$) and used to calculate the vapor permeability index (i_m), a non-dimensional measure of water vapor resistance. The ratio of i_m and clo (i_m/clo) was used to characterize the equipment’s evaporative potential [6-7].

$$R_t = \frac{(T_s - T_a)}{Q/A}\,[\mathrm{m^2K/W}] \qquad \text{Eq 1.}$$

$$1\ clo = 0.155\ [\mathrm{m^2K/W}] \qquad \text{Eq 2.}$$

$$R_{et} = \frac{(P_{sat} - P_a)}{Q/A}\,[\mathrm{m^2Pa/W}] \qquad \text{Eq 3.}$$

$$i_m = \frac{60.6515 \cdot R_t}{R_{et}} \qquad \text{Eq 4.}$$

where T_s is surface temperature, T_a is the air temperature in °C or K; Q is power input in W to maintain T_s at a given set point; A is the surface area of the manikin in m^2. P_{sat} is vapor pressure in Pascal at the surface of the manikin (assuming full saturation), and P_a is vapor pressure, in Pascal, of the chamber environment.

As a component item, measurement of the cover can be done using the above principles outlined in equations 1-4. However, to include it into the full ensemble we must account for sections of the full manikin using the below set of equations.

$$Q_i = \frac{A_i \cdot (T - T_a)}{R_i} \quad \text{Eq. 5}$$

$$Q_{total} = \sum_i^n Q_i = \frac{A_{total} \cdot (T - T_a)}{R_{total}} \quad \text{Eq. 6}$$

$$\frac{A_{total}}{R_{total}} = \sum_i^n \frac{A_i}{R_i} \quad \text{Eq. 7}$$

$$R_{total} = \frac{A_{total}}{\sum_i^n \frac{A_i}{R_i}} \quad \text{Eq. 8}$$

where Q is heat loss (W); A is the surface area of the section (m^2); R is thermal resistance (m^2°C/W); T is surface temperature of the manikin (°C); i is the section number; and n is the total number of sections.

Modeling and Analysis

A biophysics-based modeling approach was used to compare the predicted thermoregulatory responses to wearing a standard military ensemble with the prototype Afghanistan military cover and the US Army patrol cover in hot and dry conditions [3]. The model used includes inputs that account for information related to the human, the environment, activity, and the biophysics of the clothing. For the purposes of this modeling and simulation, the only feature changed was the biophysics to account for the measured differences between the two covers. Collectively, the head and neck account for ~ 8% (0.14 m^2) of a total surface area of a full human manikin (1.81 m^2). Of this the uncovered face and neck account for the majority, leaving 1-2 % surface area coverage from a military cover. For the clothing modeling, a standard uniform [8] was used as the baseline and substituting the manikin head data into the whole manikin data using the set of sectional equations (Eq. 5-8) in conjunction with the whole system methods (Eq. 1-4).

The human inputs assumed a standard, healthy male, normally hydrated, heat acclimated (12 days), 170 cm; 70 kg; with a body surface area of 1.8 m^2. The modeled conditions for the environment (ambient temperature (T_a, °C), relative humidity (RH, %), mean radiant temperature (T_{mr}, °C), and wind velocity (V, m/s)) were set as typical hot and dry condition seen in Afghanistan mid-day July (33.9°C, 0% RH, 3.58 m/s) (accessed from https://weatherspark.com, 20 September 2018). Modeled activities were set to a resting condition and a moderate activity (350 W).

RESULTS

Biophysical Results

Table 1 outlines the measured results from the sweating thermal manikin head tests. Table 2 shows the values used to describe the influence of these different covers on a whole human. While differences can be observed in both the component, sweating head values (Table 1) as well as the calculated total human values (Table 2), from a biophysics perspective these are negligible.

Table 1. Sweating thermal manikin derived biophysical measures

Test	Wind Velocity (m/s)	Thermal Resistance (R_t; m^2 K/W)	Thermal Insulation (clo)	Wind Velocity (m/s)	Evaporative Resistance (R_{et}; m^2 P_a/W)	Permeability Index (i_m)	Evaporative Potential (i_m/clo)
Nude	0.59	0.090	0.58	0.62	11.33	0.48	0.83
AF	0.60	0.123	0.79	0.62	15.78	0.47	0.60
US	0.60	0.115	0.74	0.62	15.94	0.44	0.59

Table 2. Whole human biophysics for low wind (~0.5 m/s) conditions

Test Condition	Thermal Resistance (R_t; m^2 K/W)	Thermal Insulation (clo)	Evaporative Resistance (R_{et}; m^2 P_a/W)	Permeability Index (i_m)	Evaporative Potential (i_m/clo)
Standard Uniform no cover	0.181	1.17	33.51	0.33	0.28
Standard Uniform w/AF	0.186	1.20	34.21	0.33	0.27
Standard Uniform w/US	0.185	1.19	34.09	0.33	0.28

Modeling Input values

Biophysical inputs

The modeling approach used requires four calculated or estimated biophysical inputs at 1 m/s wind velocity and exponent values (^{g}) for interpreting changes in wind velocity; specifically clo 1 m/s, a clo exponent (clo^g), i_m/clo 1 m/s, and an i_m/clo wind exponent (i_m/clo^g) (Table 3) [9].

Table 3. Calculated biophysics and wind velocity coefficients (^{g}) for 1.0 m/s

Ensemble	clo	clo^g	i_m/clo	i_m/clo^g
Standard Uniform no cover	1.04	-0.245	0.387	0.339
Standard Uniform w/AF	1.06	-0.246	0.376	0.340
Standard Uniform w/US	1.05	-0.246	0.375	0.340

Metabolic cost inputs

Estimations for modeling inputs of metabolic costs [10] are shown in Table 4.

Table 4. Estimated metabolic costs for resting and a moderate walking activity

Ensemble	Rest	Exercise activity
Standard Uniform no cover	106 W	402 W (52 external work)
Standard Uniform w/AF	106 W	402 W (52 external work)
Standard Uniform w/US	106 W	402 W (52 external work)

Modeling Results

Predicted core body temperatures were made based on component and whole manikin-obtained biophysical properties (Tables 1 and 2) along with environmental inputs typical to hot dry environmental conditions, and a resting and moderate walking activity. Figures 2 and 3 show the modeled responses over a 120 minute period. Observed differences in the calculated properties exist (Tables 1 and 2) between the different covers; however, predicted thermal responses are negligible (Figures 2 and 3).

Figure 2. Predicted core body temperature response during rest

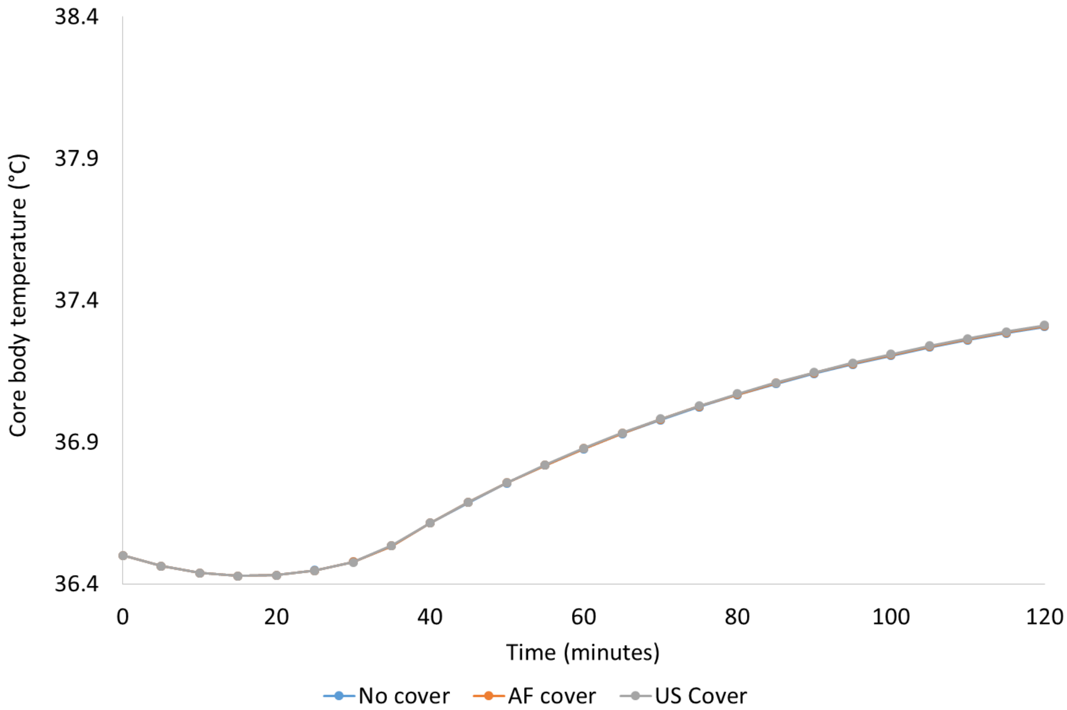
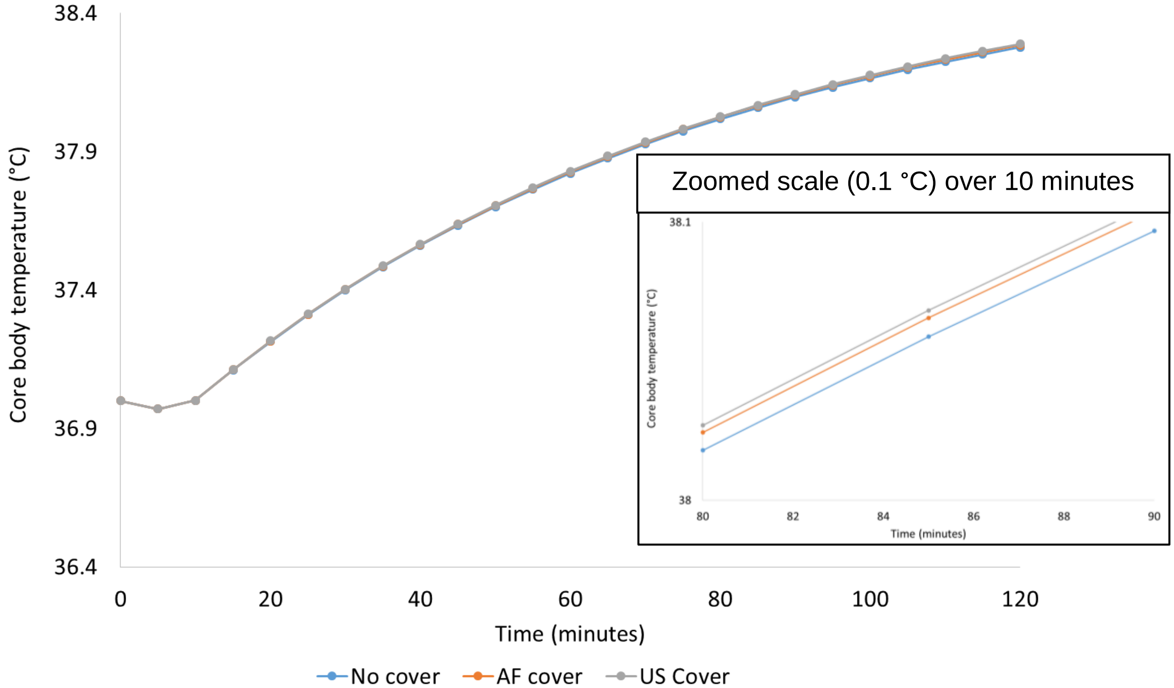


Figure 3. Predicted core body temperature response during moderate walking



DISCUSSION

While this study shows no significant differences between the two covers; it is possible for there to be human factors related differences (e.g., comfort) that are not very easily modeled [11]. These human factors related issues are by nature subjective and can have significant variability within a population. There are several human variable factors that can change these values, such as head shape, size, and hair. The biophysics of heat exchange for the cover includes three elements, air gap (R_{gap}), clothing textile (R_{cl}), and boundary layer (R_{bl}); where the total resistance is: $Resistance = R_{gap} + R_{cl} + R_{bl}$. The air gap factor is influential as a role in determining the overall value; therefore the amount of space between the head and material can change the overall thermal properties. Additionally, the biophysics can be changed by individual do to the inclusion or exclusion of hair and changed by the variable properties of hair (e.g., density, length, volume). All of these points said, as the total covered space of the cover is less than 3% of the total surface area, any of these changes would also be seen as relatively insignificant.

CONCLUSIONS

This study outlines the quantitative similarities between the two head-worn covers from a dry and evaporative heat transfer perspective. The modeling and simulation collectively describe scientific approach that clearly shows no significant differences in thermal response to wearing the two items; therefore thermal stress should not be considered as a key factor in the procurement of a cover with increased fabric.

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